EFFICIENT TECHNIQUE FOR ESTIMATING ELEVATION ANGLE WHEN USING A BROAD BEAM FOR SEARCH IN A RADAR

BACKGROUND

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5   The invention relates generally to radar systems.

In ground-based search radar systems with rotating (360°) antennas, a broad fan beam or shaped beam, e.g., a cosecant-squared beam, can be used to efficiently search over large elevation angles. This type of approach to searching for a target over a large angular search area is less time consuming than a single sequential beam approach. Typically, an elevation

10   monopulse channel and an azimuth monopulse channel provide an accurate estimate of elevation angle and azimuth angle, respectively, for a target detected by narrow pencil beams. Unfortunately, accurate elevation estimates cannot be obtained for a target detected by the broad beam. One solution to this problem is to use a stacked beam on receive. The use of a stacked beam is costly, however, as it requires one or two receivers for each beam in the stacked beam.

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SUMMARY

The present invention is therefore directed towards a mechanism for efficiently determining elevation angle information of a target detected in elevation with a broad beam such as a cosecant-squared beam.

20   In one aspect, therefore, the present invention provides methods and apparatus for determining target elevation during a radar search. The methods include determining the range of any target detected during a search with a broad beam covering a broad angular search area and, based on the determined range, transmitting consecutive beams at increasing search elevation angles in the broad angular search area and using echo signals of the consecutive

25   beams to obtain an elevation angle estimate for the target.

Embodiments of the invention may include one or more of the following features.

The broad beam can be a shaped cosecant-squared beam.   **IDS COPY**

The consecutive beams can be transmitted sequentially in time.

The first of the consecutive beams (the one at the lowest elevation angle) can be focused. Alternatively, it can be slightly defocused. The succeeding beams at successively higher elevation angles can be defocused by spoiling factors that increase with the increasing search angles. Typically all but the first one of the consecutive beams is defocused.

For a pulse Doppler radar, the transmission of the consecutive beams can include transmitting a pulse Doppler waveform which includes a set of transmit bursts, each transmit burst including a number of sub-pulses. Consecutive groups of subpulses in each transmit burst correspond to the consecutive beams. Corresponding numbered sub-pulses in each of the transmit bursts of the set have the same carrier frequency. The sub-pulses in each transmit burst can have different carrier frequencies. It is, however, possible although not generally preferred, to have the same carrier frequencies for different groups (or bursts) of sub-pulses.

Using the echo signals includes processing echo signals of the first one of the consecutive beams to detect the target. If the target is detected, an elevation angle estimate for the target is determined. Using the echo signals further includes (i) processing, in turn, echo signals of the defocused consecutive beams in the sum and difference channels until the target is detected in one of the defocused consecutive beams; (ii) using the results of the processing of the echo signals of the one of the defocused consecutive beams in which the target is detected to provide a first estimate of the elevation angle of the target; (iii) transmitting a focused beam towards the target based on the first estimate; and (iv) processing echo signals of the focused beam in the sum and difference channels to detect the target and determine a second, more accurate estimate of the elevation angle of the target.

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Particular implementations of the invention may provide one or more of the following advantages. The search mechanism is quite efficient in that it makes use of the knowledge of the range of the target and the radar system's elevation scan capability together with a time multiplexed waveform to obtain a more accurate determination of the target elevation. The time

5   multiplexed waveform transmits pulses at different elevation angles to look for the target during one dwell time. These pulses use defocused beams. The defocusing is increased with the degree of the elevation angle being searched. Such defocusing is possible and desirable because the range to the detected target decreases with increasing elevation angle. The defocusing is needed in order to efficiently cover the elevation uncertainty angle which one has after detecting the

10   target with the cosecant-squared beam or the fan beam. Once the target is located with the defocused beam, a focused beam is used to get the final, highly accurate elevation angle estimate. With an antenna having an azimuth look-back capability, it is possible to do the dwells with the defocused and focused beams during the same rotation period as that in which the target is detected. Thus, the approach of the present invention provides for efficient searching above a

15   certain low elevation angle, e.g., six degrees (or even zero degrees), without adversely impacting search frame time as with the conventional single sequential beam approach.

Other features and advantages of the invention will be apparent from the following detailed description and from the claims.

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DESCRIPTION OF DRAWINGS

FIG. 1 is a block diagram of a pulse Doppler monopulse radar system.

FIG. 2 is depiction of transmit and receive beams used by the monopulse radar system of FIG. 1 for search coverage from 0 to 70 degrees.

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FIG. 3 is a flow diagram of the operational flow of a broad beam target search that uses an elevation angle determination process for determining elevation angles for targets detected in higher elevation.

FIG. 4 is a flow diagram of the elevation angle determination process (of FIG. 3) for a
5   single detected target.

FIG. 5 is an illustration of the waveform used during the elevation angle determination process from FIG. 4.

FIG. 6 is a detailed block diagram of the detector block of FIG. 1.

FIG. 7 is a flow diagram of the elevation angle determination process for multiple
10   detected targets.

Like reference numerals will be used to represent like elements.

DETAILED DESCRIPTION

Referring to FIG. 1, a radar system 10 is shown. The radar system 10 may be a ground-
15   based radar system, but could be used on a ship, aircraft or spacecraft as well. The radar system 10 includes a transmitter 12, the output of which is delivered to an antenna 14 (in an antenna system 16) for radiation in the form of a transmit beam. The antenna 14 collects echo signals received from a target and a combiner 18 (also in the antenna system 16) combines the echo signals into receive signals 20, which are processed by a receiver 22 to detect the presence of the
20   target and determine its location in range and in angle. In the illustrated embodiment, the antenna 14 is a mechanically rotating antenna to scan in azimuth. However, the antenna 14 could also be an electronically scanned in azimuth antenna. A duplexer 24 coupled to the transmitter 12, receiver 22 and antenna 14 allows the antenna 14 to be used on a time-shared basis for both transmitting and receiving.

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Still referring to FIG. 1, the receiver 22 includes a receiver block 30 to perform RF-to-IF

conversion, amplification, A/D conversion, possibly pulse compression filtering, as well as

includes a detector block 32 and a monopulse processing block 34. The detector block 32

detects the presence of the target. More specifically, the detector block 32 performs Discrete

5   Fourier Transforms (DFTs), envelope detection and post-detection integration (video

integration), among other functions. The monopulse processing block 34 produces angle

information 35 from the output of the detector block 32. The angle information includes

information indicative of estimated elevation angle and azimuth angle.

In the illustrated embodiment, the receiver 22 is a monopulse receiver. Thus, receive

10   signals 20 include three signals, a sum (S) signal 36, an elevation difference ("ΔEL") signal 38

and an azimuth difference ("ΔAZ") signal 40. The receiver block 30 and the detector block 32

can be partitioned into three separate channels, one for each of the signals 36, 38 and 40,

respectively. Thus, receiver block 30 includes receiver blocks 48, 50 and 52, and detector block

32 includes detector blocks 54, 56 and 58. The receiver block 48 and detector block 54 form a

15   sum channel to process the sum signal 36. The receiver block 50 and detector block 56 form an

elevation difference channel to process the elevation difference signal 38. The receiver block 52

and the detector block 58 forms an azimuth difference channel to process the azimuth difference

signal 40.

The sum channel is further coupled to a threshold detect unit 60, which generates a range

20   signal from the output of the sum channel's detector block 54. The receiver 22 also includes a

detection verification block 62 as well as a range and Doppler ambiguity removal block 64.

Although not shown, the receiver 22 may be coupled to a tracker.

The output of the monopulse processing block 34 is connected to a controller/interface

68. The controller 68 provides control signals 70 to functional blocks of the system 10. In

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particular, the controller 68 enables the system 10 to perform a target search at higher elevation using a broad search beam, and to determine an accurate elevation angle estimation of a target detected by such a broad search beam, as will be described.

A "broad" elevation search beam, that is, a beam that covers a broad elevation angular search area, is a defocused (or spoiled) beam that is at least as wide as the combined beamwidths of two focused beams. Typically, however, it is much wider. A "focused" beam is a beam that has no phase modulation (for the illumination across the antenna) in the vertical direction, resulting in a beamwidth in elevation of approximately λ/H, where H is the height of the antenna. In contrast, a "defocused" beam is a beam that has phase modulation in the vertical direction. For example, a defocused beam could have a quadratic-like phase modulation.

Those aspects of the radar system 10 not described herein can be implemented according to known radar techniques, for example, those found in the "Aspects of Modern Radar," edited by Eli Brookner, (Artech House, Inc., 1988), incorporated herein by reference, and other sources. For example, monopulse techniques are discussed at some length in Chapter 5, pages 297-335, of the above-referenced Brookner text.

During a target search, the antenna 14 transmits one of two different types of beams depending on search elevation. Referring to FIG. 2, exemplary search coverage 80 includes on transmit two narrow beams 82 ("beam 1") and 84 ("beam 2") and a broad search beam 86 ("beam 3"). The narrow beams 82, 84 are used for searching at low elevation angle (e.g., from the horizon up to 5.6° in elevation, as shown) at long range. For an efficient higher elevation search, for example, when searching elevation angles from 5.6° up to 70°, the broad beam 86 is used. The broad beam 86 can be a beam such as a cosecant-squared ("CSC^2") shaped beam (as illustrated), which is a recognized beam pattern for searching large angular volume. The lower beams 82 and 84 use all three channels, in particular, the sum channel to detect the target and

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elevation and azimuth monopulse receive channels to provide estimates of the target azimuth ("AZ") and elevation ("EL") angles. The broad beam 86, e.g., the CSC^2 beam, does not use AZ or EL monopulse. Therefore, the broad beam 86 does not provide any EL angle estimates. Consequently, the beam 86 obtains good elevation coverage at the sacrifice of elevation angle

5 measurement accuracy. Furthermore, it has the important advantage of providing the large angle coverage with only three receivers, thus lowering cost. Finally, the broad beam provides such large angular coverage in a short time, thus allowing a fast volume revisit time.

In one embodiment, when illuminating the search volume with the broad beam, the two channels ordinarily used on receive for the AZ and EL monopulse with beams 1 and 2 are also

10 used for focused receive beams 88 and 90 ("beam 3A" and "beam 3B") to provide better long range coverage in a lower elevation search area of the broad beam 86, for example, in the illustrated embodiment, between the angles 5.6°and 11.2°. They also provide some elevation angle estimation, specifically, if the target is detected in either of these focused receive beams 88 and 90, an initial rough estimate of its elevation angle is available. The amplitude of the returns

15 in the two receiver channels associated with these two beams give some indication of the target's location in elevation. That is, elevation amplitude monopulse estimates can be obtained from the outputs of beams 88 and 90. When such an estimate is available, the system 10 transmits a focused beam in the direction of the target's location. This focused transmit beam has monpulse AZ and EL, and provides an accurate estimate of the target's EL and AZ angles. A pulse

20 Doppler waveform whose pulse repetition frequency ("PRF") has no range and Doppler eclipsing could be used for the focused transmit beam. If it is determined that the target is not detected by beams 3A or 3B (which provide coverage between angles 5.6° and 11.2°), the system 10 uses a special elevation angle estimation process involving additional transmit beams, including beam 92 (beam 1C), beam 94 (beam 2C), beam 96 (beam 3C), beam 98 (beam 4C) and

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beam 99 (beam 5C), at increasing search elevation angles, as will be described below with reference to FIGS. 3-7.

Referring to FIG. 3, an overview of a broad beam search process 100 that uses an elevation angle determination process for determining elevation angles for targets detected at the

5   higher elevation angles covered by beam 86 is shown. The process 100 is performed by system 10 under the control of the controller 68. To begin, the system 10 transmits a broad beam to search for the target in elevation (step 101). In the illustrated embodiment, and as was indicated earlier, the broad beam 86 is a shaped beam, more specifically, a CSC^2 beam. In one embodiment a PRF pulse Doppler waveform having range and/or Doppler ambiguities is used.

10   The system 10 detects and determines the range of a target in the broad angular elevation search area covered by the broad beam. Optionally, the system 10 uses the elevation and azimuth difference channels to form receive beams (beams 3A and 3B) to determine if the target is detected in one of those receive beams (step 102). During detection, the system uses a low false alarm probability (Pfa) setting like 10^{-6}. Upon detection, the system 10 verifies that the detection

15   is an actual echo from a real target rather than a false alarm (step 104). The verify is done using a larger Pfa of, say, 10^{-2}. This is possible as there are fewer range-Doppler cells in which to look for the target during verification. If system 10 has an azimuth scan it can look back for the verification. Alternately, the verification can be performed on the next scan (rotation). Nominally the verification would be performed with a pulse Doppler waveform having the same

20   carrier frequency and PRF as was used in the detection of the target to allow verification of the target with minimum radar energy.

If the detection verification confirms that a target is present, one or more additional pulse Doppler bursts having the same carrier frequency at different PRFs are used to remove the range-Doppler ambiguities (step 106). This removal can be done with further look backs or can occur

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on the next two scans. During this ambiguity removal stage, the Pfa is lowered below the value used for verify to a value like 10^{-4}. It is necessary to lower the Pfa because there are more range and Doppler cells to look at during ambiguity removal. Once it is determined unambiguously where the target is in range, the system 10 employs an elevation angle determination process 108

5   to locate the target accurately in terms of the target's elevation angle. While not part of the search process (and thus indicated in dashed lines), the system 10 can then perform tracking, including a firm-track initiation as well as a dedicated track or track-while-scan, in accordance with known techniques. In the illustrated embodiment, the bandwidth for steps 102, 104 and 106 is perhaps 1MHz, while the bandwidth for process 108 is 5MHz.

10   Referring to FIG. 4, which depicts process 108 for a single target detection, if it is determined that the target is detected in one of the receive beams 3A and/or 3B on transmitting the CSC^2 beam (step 120), the system 10 provides a rough estimate of the target elevation angle (step 122). The system 10 then transmits a focused beam at this location and uses the sum,ΔEL and ΔAZ channels on receive to obtain an accurate estimate of the target elevation and azimuth

15   angles (step 123). In some cases, when the target is detected in beams 3A and/or 3B, its elevation and azimuth angles can be determined accurately enough to allow focused beams to be used for verification and ambiguity removal.

        If, at step 120, it is determined that the target is not detected in the receive beams 3A and 3B but is instead at a higher angle, the system 10 uses an elevation angle estimation process 124

20   to obtain the elevation angle estimate. In the elevation angle estimation process 124, the system 10 transmits sequentially in time the focused beam 1C (or alternatively, a defocused beam 1C) and defocused beams 2C through 5C, and, for each of these beams, uses the sum,ΔEL and ΔAZ channels to obtain an estimate of the target elevation and azimuth angles (step 126). If the target is detected in one of beams 2C through 5C, the system 10 points a focused beam in the direction

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in which the target is estimated to be, and uses the elevation and azimuth difference channels and sum channel to obtain a more accurate estimate of the target elevation and azimuth angles (step 128).

Referring now to process 124 in conjunction with FIG. 5, because the target range information is known, it is possible to transmit a time-multiplexed pulse Doppler waveform which has no range or Doppler eclipsing. Such a waveform is shown in FIG. 5. Referring to FIG. 5, a pulse Doppler waveform 130 includes a set of "k+1" transmit bursts 132, with each transmit burst 132 having "i" transmit sub-pulses 134. In the illustrated embodiment, "i" and "k+1" are selected to be ten (10) and twenty-one (21), respectively. In the example shown, the waveform 130 is transmitted in a total time of 6.3 ms with a PRF of 3.33kHz.

A group of sub-pulses, denoted generally by sub-pulse group "j", are used for each of the beams 1C through 5C. In the illustrated embodiment, there are two (2) sub-pulses in a group j. The sub-pulse pairs for beam 1C, beam 2C, beam 3C, beam 4C and beam 5C are indicated by reference numerals 136 (j=1), 138 (j=2), 140 (j=3), 142 (j=4) and 144 (j=5), respectively. In the example shown, each sub-pulse duration 146 is 3.85 μs, and the inter-sub-pulse spacing 148 is 2.15 μs. Sub-pulses 1 and 2 in pair 136 are used for transmission into beam 1C, which is a focused beam. Sub-pulses 3 and 4 in pair 138 are used for transmission into beam 2C, which is a defocused beam in elevation. Sub-pulses 5 and 6 in pair 140 are used for transmission into beam 3C, which has a greater defocusing in elevation. Sub-pulses 7 and 8 in pair 142 are used for beam 4C, which has an even further defocusing in elevation. Finally, sub-pulses 9 and 10 in pair 144 are used for transmitting into beam 5C, which has a still further defocusing in elevation. In the illustrated embodiment, beams 2C, 3C, 4C, and 5C are defocused in elevation by spoiling factors of 1.25, 2.0, 4.0 and 6.5, respectively. It is possible to increase the defocusing with increasing elevation of the beam because the targets are at closer range for the higher elevation

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beams. The ith sub-pulse (where i = 1 through 10) for of each group k has the same carrier

frequency. Moreover, the 21 sub-pulses i for i=1 form a coherent pulse Doppler waveform

(burst) of duration 6.3ms, which typically is the dwell time on target. The same is true for i=2, 3,

etc. The frequency for sub-pulses in each pair j, for example, sub-pulse 1 and sub-pulse 2 of pair

5   j=1, differ, however. This is done to provide frequency diversity for more efficient target

detection. The spoiling of the beams is chosen so as to provide the needed coverage in elevation,

while at the same time maintaining a high enough signal-to-noise (SNR) ratio from each

coherent burst (in this case, consisting of 21 sub-pulses) for target detection and angle

estimation, of like greater than 11dB, after pulse compression and coherent pulse Doppler

10   processing of each of the 21 sub-pulse bursts that form the time-multiplexed pulse Doppler burst

waveforms.

Because the range of the target is known, it is also known when the echo from each of the

sub-pulses will be returned. For example, it is known when the echo for sub-pulse 1 will be

returned. In addition, the elevation angle at which the echo is expected is also known, it having

15   been transmitted using beam 1C so it can be expected to come back at the same angle as

beam1C. Hence when the echo is expected, a receive beam having the same elevation angle as

that used on transmit for beam 1C (which in this case is a focused beam) is formed. This beam

will have, in addition to a sum beam channel, a delta AZ and delta EL channel (these channels

being assumed available). Consequently, it is possible to process the echo from the sub-pulse 1.

20   The echo from sub-pulse 2 will arrive at a known time after sub-pulse 1, this time being 6 µs in

the illustrated waveform. It will also arrive in receive beam 1C because transmit beam 1C was

used to transmit it. Most importantly, the echo from sub-pulse 2 doesn't overlap the echo from

sub-pulse 1. Thus, it is possible to timeshare the same three receivers for sub-pulses 1 and 2,

which have different carrier frequencies. As already indicated different carrier frequencies are

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used for sub-pulses 1 and 2 in order to make the target fluctuate from sub-pulse to sub-pulse to enhance target detectability. The sub-pulses in different beams have different frequencies to eliminate the possibility of interference of the echoes from the different beams 1C to 5C.

Referring to FIG. 6, an exemplary implementation of the detector block 32, which

5 includes sum detector 54, elevation difference detector 56 and azimuth difference detector 58, as discussed above, is shown. Each of the three channels includes digitized samples of the compressed echo signal sub-pulses (indicated, for each pair j, as "$e_{j,k+1}$") received from the receiver block 30. The k+1 digital samples of a given sub-pulse i of a specific sub-pulse pair j for a given range (that is, $e_{i,0}$, $e_{i,1}$, ..., $e_{i,20}$) are transformed by a Discrete Fourier Transform

10 (DFT) 152 to produce amplitude and phase values amplitude b_i and phase δ_i for several Doppler cells. Similarly the k+1 sub-pulses i+1 of the same sub-pulse pair j (that is, $e_{i+1,0}$, $e_{i+1,1}$, ..., $e_{i+1,20}$) are processed to produce the amplitude and phase b_{i+1} and δ_{i+1} for several Doppler cells and for range cells covering the uncertainty in our knowledge of the target location. These two DFT's are processed by separate DFTs, for example DFT 152a for the k+1 i sub-pulses and DFT

15 152b for the k+1 i+1 sub-pulses in the pair j, as shown. Alternately, the sub-pulses in the pair can be processed in a time-sharing manner by a single DFT. The magnitudes of each of the values is selected by a corresponding envelope detector 154, and the magnitudes b_i and b_{i+1} for the sub-pulses in the pair are combined by a summer 156 to produce a single detector output value (magnitude) b_{jv} 158 for the jth pair. For simplicity, only envelope detector and summer

20 functionality for a single sub-pulse pair in each of the different channels is shown. This calculation of b_{jv} is performed for the several range cells covering the uncertainty in our knowledge of the target.

Thus, for the first transmit beam 1C, the sum detector's DFT 152a handles sub-pulses i= 1 (with frequency F1) and DFT 152b handles sub-pulses 2 (with frequency F2). The DFT 152a

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produces, from the k+1 sub-pulses where k=0, 1, 2, ..., 20, for example, b_1. The DFT 152b does likewise for sub-pulse 2 to produce b_2. These are then added to form b_{1v}. This is calculated for several range cells as indicated above. For each range cell one obtains b_1's and b_2's for several Doppler cells.

5   This processing is performed in each of the sum, elevation difference and azimuth difference detectors, as shown in the figure. The outputs of the detector block 32 are used to detect (via the threshold detect unit 60) the target and, in turn, using the monopulse processing unit 34, to estimate the target's elevation and azimuth angles. If, for example, the threshold detect unit 60 detects the target for sum detector output value $b_{1v}(S)$ (that is, for j=1), the

10   monopulse processing unit 34 will take the corresponding elevation difference detector output $b_{1v}(\Delta EL)$ and uses the ratio $b_{1v}(\Delta EL)/b_{1v}(S)$ to determine an estimate of the elevation angle, θ_{EL}. The azimuth angle can be produced in the same manner.

In the example above, the target is detected in beam 1C (j=1). If the target is not detected in the echoes from beam 1C, echoes from beams 2C, 3C, 4C and 5C are examined in turn to

15   determine if the target is present in those beams. Like the echoes from sub-pulses 1 and 2, the echoes from sub-pulses in the sub-pulse pairs for the other beams, e.g., sub-pulses 3 and 4 of beam 2C, do not overlap each other or echoes from any of the other sub-pulses. The burst of sub-pulses in each consecutive sub-pulse pair are processed using the same channels that were used for sub-pulses 1 and 2 of beam 1C. For beams 2C, 3C, 4C and 5C, the receive beams are

20   spoiled by the same amount in elevation on receive as they were spoiled on transmit. If the target is detected in beam 1C, because it is a focused beam an accurate AZ and EL angle estimate is obtained. If the target is detected in beam 2C through 5C, the estimate of the target's elevation and azimuth angles are not as accurate as would be obtained with a focused beam. As a result, if the target is detected in one of these defocused beams, and as indicated above with

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reference to step 128, a focused beam is transmitted in the direction of the target (based in the initial estimate) using a simple pulse Doppler waveform (or time-multiplexed pulse Doppler waveform in order to obtain a track update on other targets at the same time for the case where other targets exist, as will be discussed shortly). This focused beam on receive has a ΔAZ and

5   ΔEL channel for estimating the target AZ and EL angles. The echo from this focused beam observation is very accurate as the beam is focused and monopulse channels are being used.

For the angle estimates expected with the defocused beams, the first estimate is like 0.20 degrees to 0.48 degrees followed by the second estimate with the focused beam of 0.17 degrees. After the video integration, the SNR ratio in all cases for the defocused beam is typically greater

10   than or equal to 11dB. For the focused beam, the SNR is even better than for the defocused beam.

FIG. 7 shows an embodiment of elevation angle determination process 108 (from FIG. 4), indicated as elevation angle determination process 108', which assumes that multiple targets are detected. First, the process 108' determines if the targets are detected in beams 3A/3B (lower

15   elevation search area) (step 160). If so, the process 108' obtains a first rough estimate of the elevation and azimuth angles for the lower elevation target detected in beam 3A and/or 3B (step 162). The process 108' determines if at least one target is detected in the broad beam search area above beams 3A and 3B (step 163). If detection of such higher elevation target occurred, the process 108' performs step 126 (from FIG. 4) for the target detected at the higher elevation (step

20   164). If a target is detected in any of the unfocused beams, the process 108' transmits a focused beam in the direction of that target as well as the target detected in beams 3A or 3B according to the respective first (rough) estimates of each target's elevation and azimuth angles (step 166). Preferably, if possible, a time-multiplexed pulse Doppler waveform like the one used for the five consecutive beams (shown in FIG. 5) may be used to transmit the focused beams. In this

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instance, however, j is equal to the number of targets instead of five. The use of the time-multiplexed pulse Doppler beam in this instance assumes that the chosen PRF and carrier frequency do not result in any range eclipsing (overlapping transmit and echo pulses) or Doppler blindness (that occurs when the PRF line up with the target Doppler). After the focused beams

5   are transmitted, the sum and elevation/azimuth difference channels for each transmitted focused beam are used to obtain a second, more accurate estimate of the target elevation and azimuth angles (step 168.)

Otherwise, if all targets are in the search area above beams 3A and 3B, the process 108' transmits a focused beam (beam 1C) and the four unfocused beams in the broad search area

10   above beams 3A/3B, and examines the returned echoes for each beam, in turn, until either all targets are detected or returned echo signals have been examined (step 170). This step may be repeated using a different PRF and frequency for the set of five beams, if necessary, to find all of the targets (step 172). The process 108' uses the sum elevation/azimuth difference channels for each transmitted beam in which a target is detected to obtain an estimate of that target's elevation

15   and azimuth angles (step 173). If any targets are detected in any of the unfocused beams, the process 108' transmits a focused beam in the direction of each such target according to the first (rough) estimate of that target's elevation and azimuth angles (step174). If possible, when more than one focused beam is required, a time-multiplexed pulse Doppler waveform may be used to transmit the focused beams. Again, j is equal to the number of targets (in the present example,

20   j=2). Also, as was mentioned earlier with respect to step 166, the use of the time-multiplexed pulse Doppler beam assumes that the chosen PRF and carrier frequency yield no range eclipsing or Doppler blindness. After the focused beams are transmitted, the sum and elevation/azimuth difference channels for each transmitted focused beam are used to obtain a second, more accurate estimate of the target elevation and azimuth angles (step 176.)

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Other embodiments are within the scope of the following claims. For example, it will be understood that the search process 100 need not make use of receive beams 3A and 3B. Without the examination of these beams, it will be appreciated that the process 108 becomes the same as process 124, but with possibly a greater number of transmit beams involved, for example, 7

5   beams instead of 5, starting from the same elevation angle as the broad beam (5.6 degrees in the example illustrated in FIG. 2). Also, the number of focused and unfocused beams that are used may vary. It will be further understood that such parameters as PRF, beam spoiler factor and beamwidth can be adjusted as well to achieve optimal performance for a given system design. In addition, while the described embodiment includes an azimuth difference channel for

10   determining azimuth angle, it will be appreciated that elevation angle determination requires, at the minimum, a sum and an elevation difference channel. That is, an azimuth difference channel may not be needed. The azimuth of the target in this case can be obtained from the change in amplitude of the burst waveform with scan angle across the target. As most monopulse designs have both difference channels, the azimuth angle would of course be determined as well. Also, it

15   is not necessary that a pulse Doppler waveform be used. Instead, a single transmit burst or pulsed signal (k+1=1, that is, k=0) can be used.

What is claimed is:

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1.   A method for determining target elevation during a radar search comprising:

determining the range of any target detected during a search with a broad beam covering a broad angular search area;

based on the determined range, transmitting consecutive beams at increasing search

5   elevation angles in the broad angular search area; and

using echo signals of the consecutive beams to determine an elevation angle estimate for the target.

2.   The method of claim 1 wherein the broad beam comprises a shaped cosecant-squared

10   beam.

3.   The method of claim 1 wherein one of the consecutive beams is a focused beam.

4.   The method of claim 1 wherein all but a first one of the consecutive beams are defocused beams.

15   5.   The method of claim 4 wherein the defocused ones of the consecutive beams are defocused by spoiling factors that increase with the increasing elevation search angles.

6.   The method of claim 1 wherein transmitting comprises:

transmitting a time-multiplexed pulse Doppler waveform which includes a set of transmit bursts, each transmit burst including a number of sub-pulses.

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7.   The method of claim 6 wherein consecutive groups of sub-pulses in each transmit burst correspond to the consecutive beams.

8.   The method of claim 7 wherein corresponding ones of the sub-pulses in each of the transmit bursts of the set have the same carrier frequency and are coherent with each other.

9.   The method of claim 8 wherein the different sub-pulses of each transmit burst have different carrier frequencies.

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10.   The method of claim 8 wherein the sub-pulses of each group of each transmit burst have different frequencies and corresponding ones of the sub-pulses in different groups for different beams can have the same carrier frequency.

10   11.   The method of claim 9 wherein all but a first one of the consecutive beams are defocused.

12.   The method of claim 9 wherein all of the consecutive beams are defocused beams.

13.   The method of claim 4 wherein using echo signals comprises:

15   processing echo signals of the first one of the consecutive beams to detect the target; and

if the target is detected, using results of the processing to determine an elevation angle estimate for the target.

14.   - The method of claim 13 wherein using echo signals further comprises:

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processing, in turn, echo signals of the defocused consecutive beams in sum and

difference channels until the target is detected in one of the defocused consecutive beams;

using the results of the processing of the echo signals of the one of the defocused

consecutive beams in which the target is detected to provide a first estimate of the elevation

5   angle of the target;

transmitting a focused beam towards the target based on the first estimate; and

processing echo signals of the focused beam in the sum and difference channels to detect

the target and determine a second, more accurate estimate of the elevation angle of the target.

10   15.   The method of claim 14 further comprising:

using receive beams received by available elevation and azimuth difference channels for

a lower elevation search area covered by the broad beam at an elevation angle below that at

which the consecutive beams are transmitted and prior to the transmission of the consecutive

beams, to determine whether any targets are detected in the lower elevation search area; and

15   if multiple targets are detected and at least one of the multiple targets is detected in the

lower elevation search area as a lower elevation target, then performing the steps of:

obtaining a rough elevation angle estimate for the lower elevation target; and

transmitting a focused beam towards the lower elevation target based in the rough

estimate.

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16.   The method of claim 15 wherein transmitting the focused beam towards the lower

elevation target based on the rough estimate occurs in a single time-multiplexed pulse Doppler

waveform.

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17.   The method of claim 15 further comprising:

if multiple targets are detected and all of the multiple targets are detected in the broad

angular search area above the lower elevation search area, then performing the steps of:

5   processing, in turn, echo signals of the defocused consecutive beams in sum and

difference channels until either all of the multiple targets are detected or all of the echo signals of

the defocused consecutive beams have been processed;

if all of the multiple targets are not detected with one pulse repetition frequency (PRF),

then repeating the steps of transmitting consecutive beams with a different PRF and processing

10   the echo signals of each consecutive beam until all of the multiple targets are detected;

using the results of the processing steps to provide first estimates of the elevation angle of

each target;

transmitting a focused beam towards each target based on the first estimate of such target;

and

15   processing echo signals of the focused beams in the sum and difference channels to detect

each target and determine a second, more accurate estimate of the elevation angle of each target.

18.   The method of claim 17 wherein transmitting the focused beam towards each target

occurs in a single time-multiplexed pulse Doppler waveform.

20

19.   The method of claim 1 wherein transmitting comprises:

transmitting a time-multiplexed pulse Doppler waveform which includes a set of transmit

bursts, each transmit burst including the same number of sub-pulses.   --

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20. The method of claim 1 wherein transmitting comprises:

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transmitting a waveform comprising a single transmit burst.

5   21. The method of claim 20 wherein consecutive groups of sub-pulses in the transmit burst correspond to the consecutive beams.

22. The method of claim 21 wherein corresponding ones of the sub-pulses in each of the transmit burst of the set have the same carrier frequency and are coherent with each other.

23. The method of claim 22 wherein the different sub-pulses of the transmit burst have different carrier frequencies.

10   24. The method of claim 22 wherein the sub-pulses of each group of the transmit burst have different frequencies and corresponding ones of the sub-pulses in different groups for different beams can have the same carrier frequency.

25. The method of claim 23 wherein all but a first one of the consecutive beams are

15   defocused.

26. The method of claim 23 wherein all of the consecutive beams are defocused beams.

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27.   The method of claim 1 further comprising: **IDS COPY**

using one or more pencil beams to detect the target at elevation angles lower than

those covered by the broad beam.

5   28.   The method of claim 1 wherein transmitting comprises transmitting the consecutive

beams sequentially in time.

29.   A method for determining target location during a radar search comprising:

determining the range of any target detected during a search with a broad beam

10   covering a broad angular search area;

based on the determined range, transmitting consecutive beams at increasing search

elevation angles in the broad angular search area; and

using echo signals of the consecutive beams to determine at least one angle estimate

for the target.

15

30.   The method of claim 29 wherein the at least one angle estimate comprises an

elevation angle estimate and an azimuth angle estimate.

31.   A radar system comprising:

20   means for determining the range of any target detected during a search with a broad beam

covering a broad angular search area;

means for transmitting consecutive beams at increasing search elevation angles in the

broad angular search area for the determined range; and

22

means for using echo signals of the consecutive beams to determine an elevation angle estimate for the target.

32.   The radar system comprising:

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5   an antenna system;

a transmitter coupled to the antenna system;

a receiver coupled to the antenna system;

a controller to control the transmitter, receiver and antenna system;

wherein the receiver, responsive to control signals from the controller, operates to

10   determine the range of any target detected during a search with a broad beam covering a broad

angular search area;

wherein the transmitter, responsive to signals from the controller, operates to transmit,

via the antenna system, consecutive beams at increasing search elevation angles in the broad

angular search area for the determined range; and

15   wherein the receiver, responsive to control signals from the controller, operates to use

echo signals of the consecutive beams received via the antenna system to determine an elevation

angle estimate for the target.

33.   The radar system of claim 32 wherein the broad beam comprises a shaped cosecant-

20   squared beam.

34.   The radar system of claim 32 wherein at least one of the consecutive beams is a focused

beam.

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35. The radar system of claim 32 wherein all but a first one of the consecutive beams are defocused beams.

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5   36. The radar system of claim 32 wherein all of the consecutive beams are defocused beams.

37. The radar system of claim 35 wherein the defocused ones of the consecutive beams are defocused by spoiling factors that increase with each consecutive beam.

10   36. The radar system of claim 32 wherein the transmitted consecutive beams are transmitted in a single time multiplexed pulse Doppler waveform which includes a set of transmit bursts, each burst including a number of sub-pulses with each sub-pulse forming a pulse Doppler waveform.

15   37. The radar system of claim 36 wherein consecutive groups of sub-pulses in each transmit burst correspond to the consecutive multiple beams.

38. The radar system of claim 37 wherein a corresponding ones of the sub-pulses in each of the transmit bursts of the set have the same carrier frequency and are coherent with each other.

39. The radar system of claim 37 wherein the sub-pulses of each transmit burst have different carrier frequencies.

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40.   The radar system of claim 39 wherein the sub-pulses of each group of each transmit burst

have different frequencies and corresponding ones of the sub-pulses in different groups for

different beams can have the same carrier frequency.   **IDS COPY**

41.   The radar system of claim 39 wherein all but a first one of the consecutive beams are

defocused.

42.   The radar system of claim 39 wherein all of the consecutive beams are defocused beams.

43.   The radar system of claim 32 wherein the echo signals are used to process echo signals of

the first one of the consecutive beams to detect the target and, if the target is detected, determine

from the results of the processing an elevation angle estimate for the target.

44.   The radar system of claim 43 wherein the echo signals are used to process, in turn, echo

signals of the defocused consecutive beams in sum and difference channels until the target is

detected in one of the defocused consecutive beams, obtain from the results of the processing of

the echo signals of the one of the defocused consecutive beams in which the target is detected a

first estimate of the elevation angle of the target, transmit a focused beam towards the target

based on the first estimate and process echo signals of the focused beam in the sum and

difference channels to detect the target and determine a second, more accurate estimate of the

elevation angle of the target.

45.   The radar system of claim 32 wherein the focused beam is transmitted as a time-

25

multiplexed pulse Doppler waveform which includes a set of transmit bursts, each transmit burst including the same number of sub-pulses.

46.   The radar system of claim 32 wherein the focused beam is transmitted as a pulsed signal comprising a single transmit burst.

47.   The radar system of claim 46 wherein consecutive groups of sub-pulses in the transmit burst correspond to the consecutive beams.

48.   The radar system of claim 47 wherein corresponding ones of the sub-pulses in each of the transmit burst of the set have the same carrier frequency and are coherent with each other.

49.   The radar system of claim 48 wherein the different sub-pulses of the transmit burst have different carrier frequencies.

50.   The radar system of claim 48 wherein the sub-pulses of each group of the transmit burst have different frequencies and corresponding ones of the sub-pulses in different groups for different beams can have the same carrier frequency.

51.   The radar system of claim 49 wherein all but a first one of the consecutive beams are defocused.

52.   The radar system of claim 49 wherein all of the consecutive beams are defocused

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beams.

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53. The radar system of claim 32 wherein one or more pencil beams are used to detect the target at elevation angles lower than those covered by the broad beam.

5

54. A radar system for determining target location during a radar search comprising:

means for determining the range of any target detected during a search with a broad beam covering a broad angular search area;

means for transmitting consecutive beams at increasing search elevation angles in the

10 broad angular search area based on the determined range; and

means for using echo signals of the consecutive beams to determine at least one angle estimate for the target.

55. The radar system of claim 54 wherein the at least one angle estimate comprises an

15 elevation angle estimate and an azimuth angle estimate.

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MULTIPLE RADAR COMBINING FOR INCREASED RANGE, RADAR SENSITIVITY AND ANGLE ACCURACY

BACKGROUND

5   The invention relates generally to radar, and more particularly, to radar systems having

multiple antennas.

In the field of radar systems technology, there continues to be a need for improved

capability to handle potential lower cross section as well as longer range targets. In the past, this

need has been met by developing larger, more sensitive (and thus more costly) radars.

10

SUMMARY

The present invention features a technique for combining multiple radars for increased

sensitivity and range.

In one aspect, therefore, a method of radar processing includes: radiating a first signal

15   beam from an antenna of a first radar in the direction of a target; radiating a second signal beam

from an antenna of a second radar in the direction of the target; receiving echo signals from the

first signal beam at the first and second radars; receiving echo signals from the second signal

beam at the first and second radars; processing the echo signals received at the first radar to

produce first radar processed echo signals; processing the echo signals received at the second

20   radar to produce second radar processed echo signals; and combining the first and second radar

processed echo signals to form an aggregate value.

Particular implementations of the invention may provide one or more of the following

advantages. The present invention addresses a need for increased range and sensitivity to handle

lower cross section and longer range targets as they appear in the future without having to build

25   larger radars for them in the near term. The increased sensitivity is achieved by combining low

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sensitivity, lower cost radars with minor modification to achieve the higher sensitivity and

increased range.

Other features and advantages of the invention will be apparent from the following

detailed description and from the claims.

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a multi-radar combining system.

FIG. 2 is a conceptual depiction of the multi-radar combining system showing the paths

of the transmit signal beams and corresponding echo signals for two radars.

10   FIG. 3 is a block diagram of a portion of the system modified to combine coherently the

echo signals for the same carrier frequency and combine the results (different carrier

frequencies) using video integration.

FIG. 4 is a block diagram of an exemplary digital implementation of the multi-radar

combining system.

15   FIG. 5 is a table that shows sensitivity improvement for search and tracking modes based

on different techniques of combining two radars.

Like reference numerals will be used to represent like elements.

DETAILED DESCRIPTION

20   Referring to FIG. 1, a multi-radar combining system 10 that combines radars to achieve

enhanced capability, in particular, increased range and sensitivity, is shown. The system 10

includes multiple radars 12, shown in the illustrated embodiment as two radars 12a and 12b.

Here radar 12b is the "master", although the roles could be reversed. The radars 12a and 12b

each include a transmitter, shown as transmitter 14a and transmitter 14b, respectively. The

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outputs of the transmitters 14a and 14b are delivered to respective antennas 16a, 16b for

radiation in the form of a transmit beam directed at a target (indicated by reference numeral 18).

In the illustrated embodiment, the antennas 16a, 16b are rotating antennas; however, a stationary

antenna could also be used. The antennas 16a, 16b collect echo signals received from the target,

5   and the echo signals (which may be combined into monopulse receive signals) are processed by

respective receivers 20a, 20b to detect the presence of the target and determine its location in

range and in angle. In radar 12a, a duplexer 22a coupled to the transmitter 14a, receiver 20a and

antenna 16a allows the antenna 16a to be used on a time-shared basis for both transmitting and

receiving. A duplexer 22b, coupled to the transmitter 14b, receiver 20b and antenna 16b,

10   provides the same functionality (as duplexer 22a) in radar 12b.

Still referring to FIG. 1, the receivers 20a and 20b include a low-noise amplifier ("LNA")

23a and a LNA 23b, respectively. The LNA 23a (of receiver 20a) is coupled to down converters

24a-1 and 24a-2, and the LNA 23b (of receiver 20b) is coupled to down converters 24b-1 and

24b-2. The down converters 24a-1, 24a-2, 24b-1 and 24b-2 (more generally, down converters

15   24) perform RF-to-IF conversion. Each of the receivers includes a receiver exciter ("REX"), a

REX 25a in receiver 20a and a REX 25b in receiver 20b. The REX 25b of the master radar 12b

(master REX) provides both transmit carrier frequencies f_1 and f_2, with their modulations, and

local oscillator signals LO_1 and LO_2 (indicated collectively by reference numeral 26), to radars

12a and 12b. In the example shown, with radar 12b serving as the master radar, REX 25a of

20   radar 12a is in "by-pass" mode, that is, it does not operate as a REX but merely distributes within

radar 12a the signals generated by REX 25b. In receiver 20a, the down converter 24a-1 and the

down converter 24a-2 are connected to a signal processor 27a-1 and a signal processor 27a-2,

respectively. In receiver 20b, the down converter 24b-1 and the down converter 24b-2 are

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connected to a signal processor 27b-1 and a signal processor 27b-2, respectively. The signal

processors 27a-1, 27a-2, 27b-1 and 27b-2 (generally, signal processors 27) perform filtering,

possibly including pulse compression filtering. The signal processors 27 are further connected to

envelope detectors, more specifically, signal processor 27a-1 and signal processor 27a-2 are

5   connected to envelope detector 28a-1 and envelope detector 28a-2, respectively, while signal

processor 27b-1 and signal processor 27b-2 are connected to envelope detector 28b-1 and

envelope detector 28b-2, respectively.   The four envelope detected signals are added (video

integrated) by a combiner 30 and passed to a threshold detector 32 for detection. The threshold

detector 32 is coupled to and provides detection information to other conventional radar system

10   elements, e.g., a tracker 34 and a display 36, as shown.

As indicated above, system 10 combines receive signals of radars 12a, 12b in a manner

that achieves greater sensitivity gain and increased range. Referring now to FIG. 2 in

conjunction with FIG. 1, the radars 12a, 12b to be combined are positioned in fairly close

proximity to each other. The phase centers of the antenna 16a and the antenna 16b (in radar 12a

15   and radar 12b, respectively), are spaced by a distance "D". The distance D is a flexible

parameter. A small value for D may be selected to simplify the processing of the echo signals.

If a larger distance is chosen, delays may be needed so that the echo signals can be added

correctly (to within a fraction of a pulse width) during processing. Also, if coherent integration

is used ($f_1=f_2$), the effects of interferometric lobing become a concern when there is too much

20   spacing between the radars.   If the distance D is somewhat larger than the width "W" of the

antenna 16, then a large interferometer baseline is formed when coherent combining on receive

is used (as discussed shortly), with the result that the angle accuracy will be improved, in some

cases by an order of magnitude.

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Referring again to FIG. 1, the rotation of the antennas of the multiple radars are synchronized by a synchronization signal provided by an azimuth servo 37b (in radar 12b) to an azimuth servo 37a (in radar 12a) so that the beams of the radars look in the same direction, to within a fraction of a beamwidth. The radars nominally radiate identical transmit signal beams

5 (e.g., beams 40 and 42 for radars 12a and 12b, respectively) at the same time. The beams could, however, be different. The carrier frequencies f_1 and f_2 are different where incoherent transmit operation and incoherent receiver combining is used. The carrier frequencies f_1 and f_2 will be the same if coherent transmit operation and coherent receiver combining for all signals is desired, as discussed later. When the carrier frequencies f_1 and f_2 are different, they may differ sufficiently

10 so that they do not interfere with each other and can be separated from each other in the radar receivers, yet are close enough to allow the same phase shift commands for a phased array antenna. Also, they may differ sufficiently to provide frequency diversity, i.e., the echo amplitudes are then independent at the two frequencies. In addition, the use of different carrier frequencies helps to avoid interferometric lobing, which is not desirable during search (and may

15 not be desirable for tracking, either, if the radars are too far apart). The echoes of the transmitted signals from both radars are received by both radars.

FIG. 2 shows the path of the echo signals for both radars. Still referring to FIGS. 1 and 2, echoes from a transmit beam radiated by the antenna of radar 12a towards the target 18 are received at radar 12a, as indicated by reference numeral 50a (echo signals "e_{11}"), and are

20 received at radar 12b, as indicated by reference numeral 50b (echo signals "e_{12}"). Similarly, the echoes of the transmitted signal from radar 12b are received at radar 12a, as indicated by reference numeral 52a (echo signals "e_{21}"), and are received at radar 12b, as indicated by reference number 52b (echo signals "e_{22}"). These four echoes 50a, 50b, 52a, 52b, are pulse

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compressed and pulse Doppler processed (if appropriate) in the appropriate signal processors 27

to produce processed echo signals s_{11} 54a, s_{12} 54b, s_{21} 56a, s_{22} 56b, respectively, as shown in

FIG. 1. The four processed echoes are then envelope detected and video integrated to produce

video integrated signals v_{11} 57a, v_{12} 57b, v_{21} 58a and v_{22} 58b, respectively. These four signals

5   are combined to produce an aggregate value 59. It will be understood from the figure that the

receiver of radar 12a handles the processing of signals e_{11} 50a and e_{21} 52a to produce v_{11} 57a and

v_{21} 58a, respectively, while the receiver of radar 12b handles the processing of signals e_{12} 50b

and e_{22} 52b to produce v_{12} 57b and v_{22} 58b, respectively.

In the embodiment illustrated in FIG. 1, the four echoes are combined incoherently in the

10   radar receiver. Other techniques may be used to combine the echo signals as well. One example

is shown in FIG. 3. Referring to FIG. 3, the combiner 30 of the receiver is suitably adapted to

allow the processed signals having the same carrier frequency, e.g., s_{11} and s_{12}, to be added

coherently. Thus, s_{11} and s_{12} can be added coherently by a first adder 60a, and s_{21} and s_{22} can be

added coherently by a second adder 60b. The resulting sum signals $s_{11}+s_{12}$ ("S_1") and $s_{21}+s_{22}$

15   ("S_2") each are envelope detected by respective envelope detectors 62a, 62b. The envelope

detected values v_1 and v_2 are combined by a third adder 60c to form the final, aggregate value 59.

Generally, for the search mode, it is found that coherent addition of the type described

with reference to FIG. 3 does not provide any significant improvement in detectability over

video integration (incoherent addition). This is the case because the phases of processed echo

20   signals s_{11} and s_{12} (and s_{21} and s_{22}) are not known, and so the signals have to be added with a

bank of adders having different relative phase shifts, as will be described shortly. For the track

mode, coherent addition can provide better SNR.

The processed echo signals may be combined using different techniques when the carrier

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frequencies f_1 and f_2 are equal as well. For example, the four processed echo signals may be combined coherently (track mode), or using a combination of coherent and incoherent integration (for track or search mode also). When $f_1 = f_2$, it is only necessary to have one mixer per radar. In the illustrated embodiment of FIG. 1, for the case of $f_1 = f_2$, only one pair of mixers, for example, 24a-1 and 24b-1 (or, alternatively, 24a-2 and 24b-2), need be used. As discussed later, f_1 would be set equal to f_2 generally for a track mode only.

The potential advantage of using coherent integration is that of providing improved sensitivity (about another 3 dB to about 9 dB) for the track mode. This improved sensitivity is realized because of the coherent addition that can result in beams from radars 12a and 12b at the target for $f_1 = f_2$ when the signals from radars 12a and 12b are transmitted simultaneously. An interferometric pattern is produced on transmit. If the phase centers of the two radars are not known to a fraction of a wavelength, then more than one simultaneous transmission of the signals from radars 12a and 12b will be needed with different relative phase shifts between the signals for each transmission to ensure coherent addition at the target (or worded differently, to ensure that the target is near the peak of transmit interferometric peak). First a 0° relative phase shift would be tried. If the target is not detected (or the SNR is not as large as expected), then a 180° relative phase shift would be used. If the target is still not detected (or the SNR not large enough), a 90° relative phase shift could be used, followed finally by a 270° relative phase shift.

On receive, because the phases of the signals out of the radars 12a and 12b will not generally be known, the coherent combining will be performed using a bank of parallel channels each adding the two signals with a different relative phase shift. For example, eight phase shifts from 0° to 315° in steps of 45° could be used. After the best relative phase shift for receive was determined out of the eight possible phase shifts, the signals could be reprocessed with smaller

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phase steps to determine which gives the best SNR, so as to eventually achieve 9 dB

improvement in SNR over that obtained with one radar in the track mode.

If the phase centers of the two radars were known to a fraction of a wavelength, it would

not be necessary to use multiple transmissions with different phase shifts to get the signals from

5   the two radars to add coherently at the target, i.e., to put a transmit interferometric lobe on the

target. Instead, the phase shift needed to put a transmit and receive interferometric lobe on the

target would be determined from knowledge of the location of the target to a fraction of a

beamwidth. The target angle determination is obtained from the normal monopulse channel

signals from the radars operated with $f_1 \neq f_2$. In this case, the standard monopulse outputs of

10   radars 12a and 12b would be processed in the same way as described above (with reference to

FIG. 3) for the sum signal outputs, but now to estimate the target angle. The coherent addition

on transmit and receive can be further improved if defined by using the initial phase shifts for

transmit and receive obtained from the monopulse measurements and then searching for better

phase shifts for transmit and receive.

15   With $f_1 = f_2$ it is possible to avoid having an interferometric pattern on transmit by

transmitting the signals from radars 12 and 12b sequentially in time so as not to overlap in time

on transmit or receive. The echo signals can then be added incoherently when appropriately

delayed on receive. The sequential transmissions eliminate the need for two receivers in each

radar. The improvement in sensitivity achieved with this technique is about 6 dB.

20   Once the target is detected, it is possible to estimate that target's azimuth (or elevation)

angle very accurately. For $f_1 \neq f_2$, it is possible to determine the target's location in angle to a

fraction of a receive interferometric lobe width. This determination can be made by measuring

the phase of s_{11} relative to s_{12} and, likewise, s_{21} relative to s_{22}. Knowing these phases provides a

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very accurate estimate of the target angle, specifically to a fraction of a receive interferometric lobe width, which is much narrower than the width of the beams of each radar. The ambiguity as to which lobe the target is on is eliminated by using a normal monopulse measurement obtained with $f_1 \neq f_2$ as described above.

5   For $f_1 = f_2$, the target angle is estimated accurately by measuring the phase between the signals out of receivers 22a and 22b independent of whether the signals are transmitted from radars 12a and 12b simultaneously or sequentially.

Other implementations of the radars 12a, 12b are possible. While the block diagram of FIG. 1 is intended to be conceptual in nature, it depicts an all analog implementation for the

10   radars 12a, 12b. It will be understood, however, that the radar receiver can be designed for digital signal processing, as shown in FIG. 4.

Referring now to FIG. 4, the system 10 includes a digital signal processor 70 that receives echo signals from each of the down converters 24. In the exemplary digital processing implementation of FIG. 4, the signals correspond to in-phase ("I") and quadrature ("Q")

15   channels. The digital signal processor 70 performs digitally those functions performed by units 27, 28 and 30 of system 10 as depicted in FIG. 1. The output of the digital signal processor 70, that is, the aggregate value, can be provided to threshold detector 32, as before.

Although the digital signal processor 70, like the units 27, 28 and 30, can be separate from the radars 12a, 12b, this circuitry could reside in one or both of the radars. If included in

20   both radars, only the digital signal processor 70 in one radar operating as the master would be used during operation. The same can be said of the threshold detect 32, tracker 34 and display 36. In FIG. 4, as in FIG. 1, radar 12b is represented as the master. Any digital signal processing, threshold detect, tracking and display capability in radar 12a, to the extent that it may exist, has

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been omitted from the figure for simplification.

While only two radars are shown in the system examples of FIGS. 1 and 4, it will be appreciated that the multi-radar combining concept embodied therein can be extended to more than two radars. Also, although the radars 12a, 12b are described as rotating antennas, the

5   technique described herein also applies to radars that use non-rotating phased arrays.

FIG. 5 shows a table that provides the Signal-to-Noise Ratio (SNR) sensitivity improvement (in dB) for different techniques of combining two radars. For a non-fluctuating target, the sensitivity gain of the combined radars (relative to a single radar) is approximately 6dB for searches regardless of whether coherent or incoherent integration is used (on transmit

10   and/or receive). For track mode, when coherent integration is used on transmit and the frequency is the same for both radars (that is, $f_1 = f_2$), the strength of the signal on the target is greater by 3 dB so that the SNR is now 3 dB higher for a total gain of 9 dB over that for a single target.

For the case of a fluctuating target (Swerling-II type), it is assumed that the two radars

15   being combined as described above use carrier frequencies that differ sufficiently to provide frequency diversity. For a single look Pd of 90%, therefore, the resultant increase in sensitivity is 8.7 dB better than that of a single radar that does not use frequency diversity.

Other embodiments are within the scope of the following claims.

What is claimed is:

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1.   A method of radar processing comprising:

radiating a first signal beam from an antenna of a first radar in the direction of a

target;

radiating a second signal beam from an antenna of a second radar in the direction of

5   the target;

receiving echo signals from the first signal beam at the first and second radars;

receiving echo signals from the second signal beam at the first and second radars;

processing the echo signals received at the first radar to produce first radar processed

echo signals;

10   processing the echo signals received at the second radar to produce second radar

processed echo signals; and

combining the first and second radar processed echo signal values to form an

aggregate value.

15   2.   The method of claim 1 wherein the first and second signal beams have respective first

and second carrier frequencies which are different.

3.   The method of claim 2 wherein combining comprises combining incoherently all of

the first and second radar processed echo signals.

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4.   The method of claim 2 wherein combining comprises:

combining coherently those of the first and second radar processed echo signals that

have the first carrier frequency;

combining coherently those of the first and second radar processed echo signals that

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have the second carrier frequency; and

combining incoherently the results of the coherent combination for the first and

second carrier frequencies.

5   5.   The method of claim 1 wherein the first and second signal beams have the same

carrier frequency.

6.   The method of claim 5 wherein combining comprises:

combining coherently those of the first and second radar processed echo signals from

10   the first signal beam to produce a first result;

combining coherently those of the first and second radar processed echo signals from

the second signal beam to produce a second result; and

combining coherently the first and second results.

15   7.   The method of claim 5 wherein combining comprises:.

combining coherently those of the first and second radar processed echo signals from

the first signal beam to produce a first result;

combining coherently those of the first and second radar processed echo signals from

the second signal beam to produce a second result; and

20   combining incoherently the first and second results.

8.   The method of claim 5 wherein combining comprises:

combining incoherently those of the first and second radar processed echo signals

from the first signal beam to produce a first result;

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combining incoherently those of the first and second radar processed echo signals

from the second signal beam to produce a second result; and

combining incoherently the first and second results.

5   9.   The method of claim 8 wherein the first and second signal beams are transmitted

sequentially in time.

10.   The method of claim 1 wherein the antennas are synchronized rotating antennas.

10   11.   The method of claim 1 wherein the antennas comprise non-rotating phased arrays.

12.   A method of processing by a radar comprising:

radiating a first signal beam in the direction of a target;

receiving echo signals from the first signal beam;

15   receiving echo signals from a second signal beam radiated by a second radar in the

direction of the target, the radar and the second radar being spaced a predetermined distance

apart; and

processing the echo signals from the first and second signal beams.

20   13.   The method of claim 11 further comprising:

combining the processed echo signals with echo signals from the first and second

signal beams that have been received by the second radar and processed, to form an

aggregate value.

25   14.   A radar comprising:

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an antenna to radiate a first signal in the direction of a target;

a receiver to receive echo signals from the first signal beam and echo signals from a second signal beam radiated by a second antenna of a second radar in the direction of the target; and

5   circuitry to process the echo signals from the first and second signal beams, and to combine the processed echo signals with echo signals from the first and second signal beams that have been received by a receiver of the second radar and processed, to form an aggregate value.

10   15.   The radar of claim 14 wherein the circuitry comprises a digital signal processor.

16.   The radar of claim 14 wherein the circuitry comprises analog circuitry.

17.   The radar of claim 14 further including circuitry to synchronize rotation of the

15   antenna with the second antenna of the second radar.

18.   The radar of claim 14 wherein the first and second signal beams have respective first and second carrier frequencies which are different.

20   19.   The radar of claim 18 wherein the circuitry combines the processed echo signals using incoherent integration.

20.   The radar of claim 18 wherein the circuitry combines the processed echo signals using both coherent and incoherent integration.

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21.   The radar of claim 14 wherein the first and second signal beams have respective first and second carrier frequencies which are the same.

22.   The radar of claim 21 where the circuitry combines the processed echo signals using

5   coherent integration.

23.   The radar of claim 21 wherein the circuitry combines the processed echo signals using incoherent integration.

10   24.   The radar of claim 21 wherein the circuitry combines the processed echo signals using both coherent and incoherent integration.

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